Mapping the Hvítá-Ölfusá Watershed, Southwestern Iceland

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Introduction

The Hvítá River winds for ~140 km across southwestern Iceland, stretching from the desolate interior highlands to the verdant coastal plains. Near the end of its course, the Hvítá joins with the Sog River to form the Ölfusá, which flows into the Atlantic Ocean ~30 km later. The Hvítá-Ölfusá watershed is a jewel in Iceland's crown, occupying a key position in tourism, agriculture, wildlife habitat, and water resources. Additionally, the Hvítá region was the site of some of the largest known floods in Iceland and on Earth. ~9500 years ago, a series of jökulhlaups—also known as glacial lake outburst floods or GLOFs—drained an ice-dammed glacial lake in the highlands and surged along the river's present-day course, reaching an estimated peak discharge of 300,000 $m^3 s^{-1}$ (Tómasson, 1993). These catastrophic events left behind a suite of distinctive geomorphologic landforms clustered along the Hvítá's banks. Among the most prominent are 32-m-high Gullfoss waterfall, where the Hvítá thunders into Hvítárgljúfur, a floodwater-sculpted canyon that is 3 km long and up to 70 m deep. My dissertation research seeks to reconstruct flood timing, routing, magnitude, and frequency of the Hvítá paleofloods. For this project, I mapped and characterized surface drainage networks within the Hvítá-Ölfusá basin.

Study Area

The Hvítá River cuts through a wide range of landscapes and climates on its path to the Atlantic Ocean. The river's name translates to "white river" in Icelandic, referring to the white hue from the fine glacial sediment that chokes its waters. The Hvítá drains from lake Hvítárvatn, which is fed by an outlet glacier from Langjökull, Iceland's second-largest ice cap. Hvítárvatn is a turquoise oasis in the midst of the interior Kjölur highlands, a barren, rocky expanse that stretches between Langjökull and Hofsjökull ice caps and lies ~500-800 m above sea level. After ~50 km, the Hvítá plunges overs Gullfoss waterfall and funnels through Hvítárgljúfur canyon, after which point it flows across a relatively flat, fertile plain until it reaches the Atlantic. These lowlands are predominantly pasture and agricultural land, made possible by an extensive network of human-made drainage canals and ditches. The government subsidized wetland drainage from 1942 to 1987 to increase farmland, and roughly 30,000 km of ditches currently dissect the Icelandic lowlands (Gísladóttir et al., 2010; Arnalds et al., 2016). ~30 km from its mouth, the Hvítá joins the Sog to form the Ölfusá before finally emptying into the Atlantic.

The Hvítá-Ölfusá basin drains an area of 6190 km^2 (Pagneux et al., 2010) (Figures 1 and 2). Annual average precipitation ranges from 1350 mm in the lowlands to 3800 mm over Langjökull and Hofsjökull (Pagneux et al., 2010). With average winter temperatures below freezing and summer temperatures rarely exceeding 10° C, the drainage basin has low evapotranspiration (Icelandic Meteorological Office, 2017). The interior highlands are underlain by a rocky pavement and are largely unvegetated, except for thin soil cover and grasses along lake and river banks. The coastal plains, however, are blanketed in grass, willow bushes, and farmland, mostly for hay production.

The Hvítá-Ölfusá watershed plays a vital role in Icelandic culture and ecosystem services. Several kilometers from its mouth, the river widens to form the Flói estuary, a major nesting ground for wetland birds. Gullfoss waterfall lies at the apex of the "Golden Circle," a popular day-trip circuit from Reykjavík. It is of Iceland's most visited sites, receiving nearly one million international tourists in 2016. The river is also popular for whitewater rafting trips. Yet the Hvítá can also prove dangerous; it has flooded at least 54 times between 1825 and 2006 often due to winter ice jams, inflicting substantial damage on infrastructure along its banks (Pagneux et al., 2010).

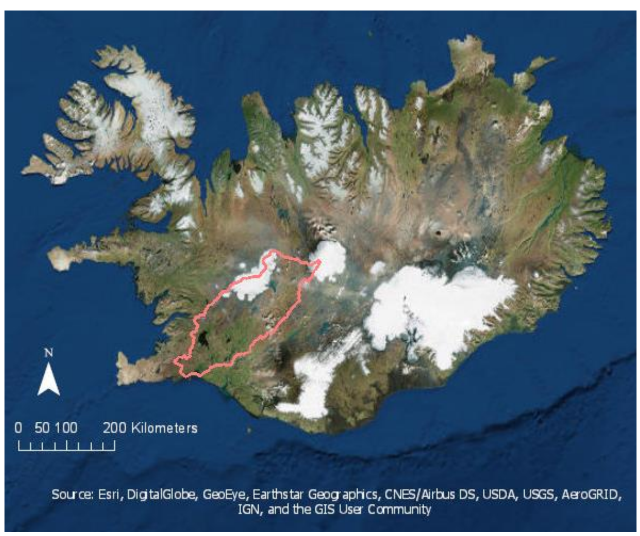

Figure 1. Iceland, with the Hvítá-Ölfusá River basin outlined in pink.

Figure 2. Hvítá-Ölfusá drainage basin with snapshots from around the drainage network.

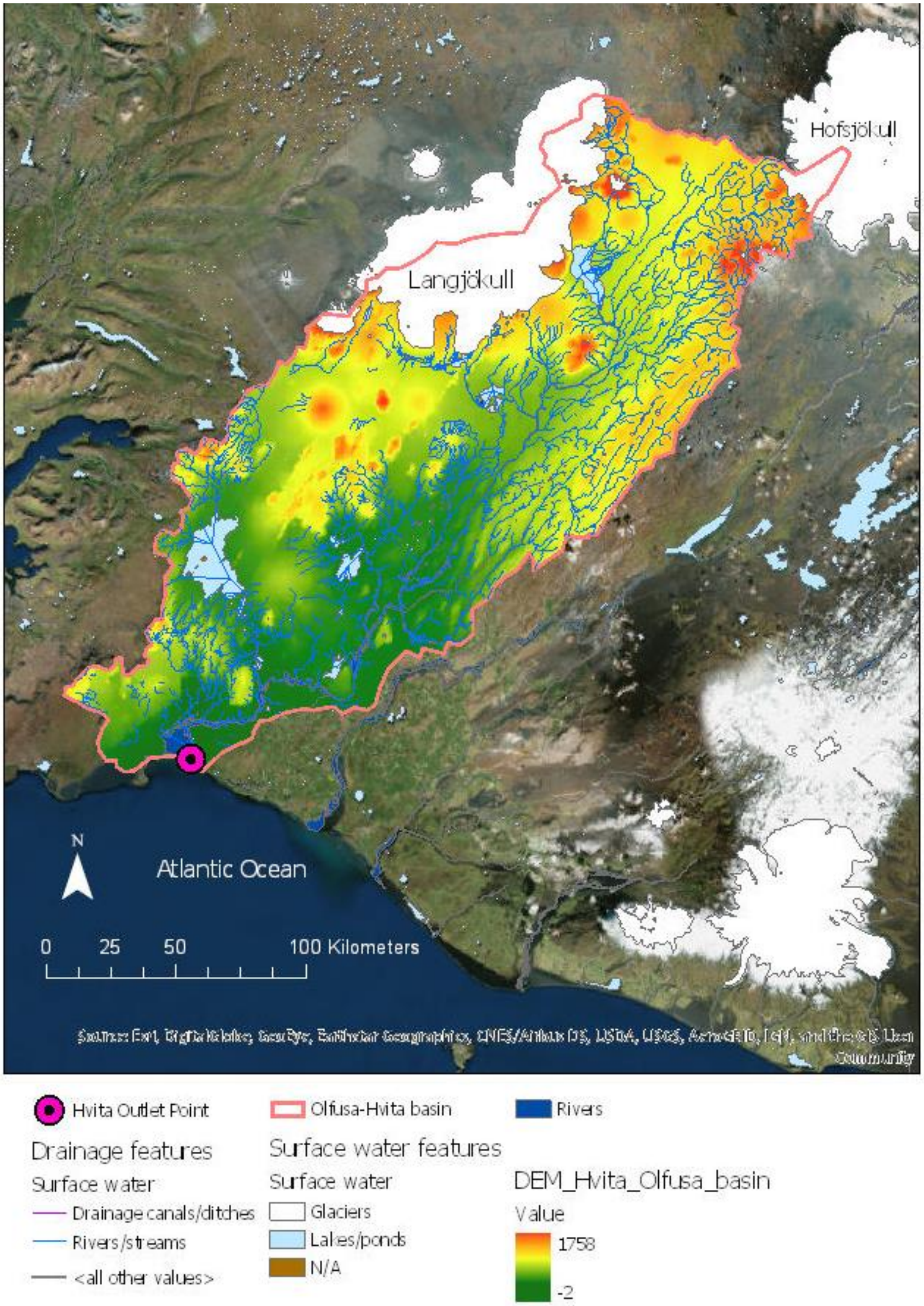

Figure 3. Drainage network and DEM layers in Hvítá-Ölfusá basin.

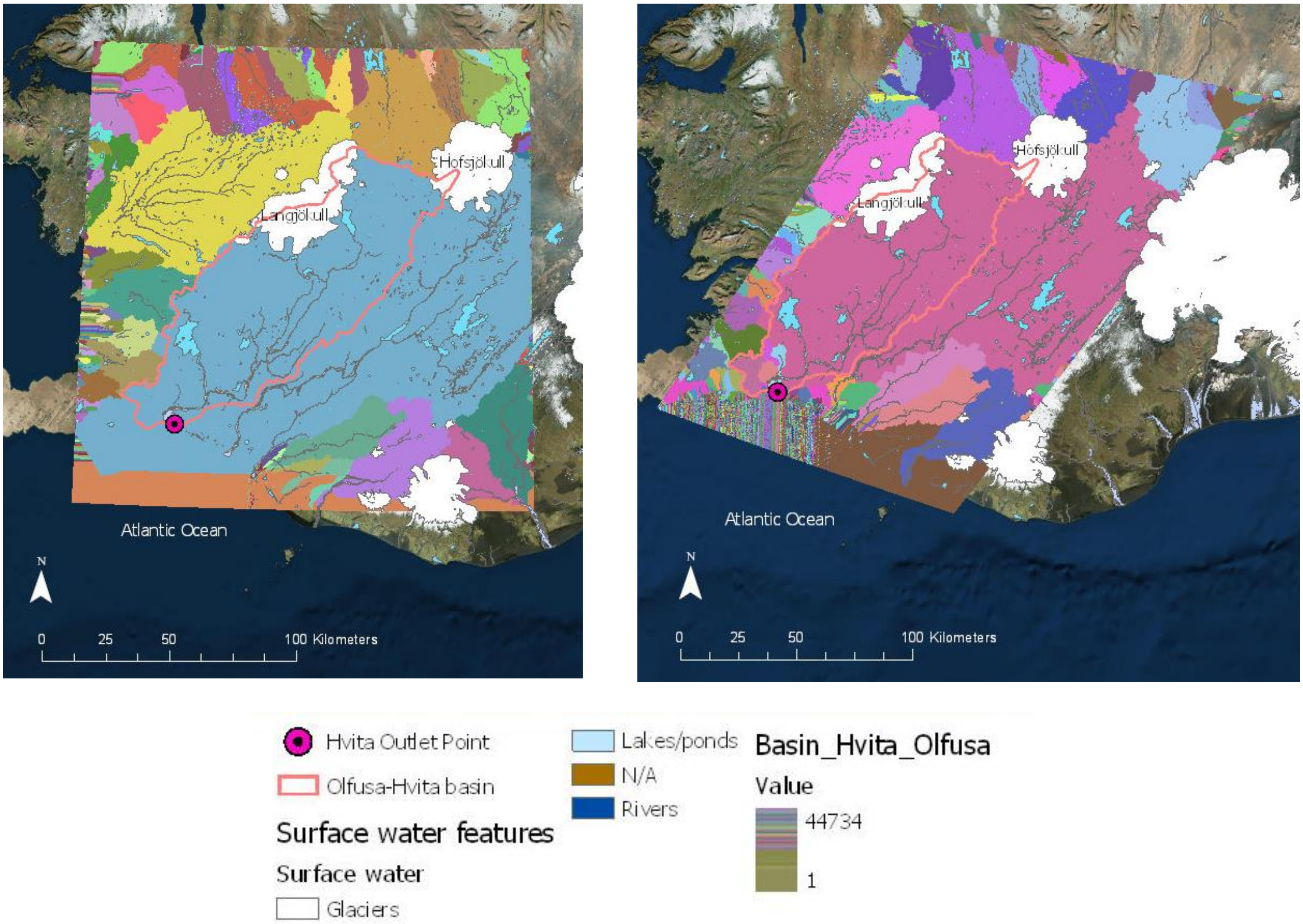

Figure 4. Two basin delineations for different spatial extents in study region. Note that different input areas sometimes result in different watershed delineations.

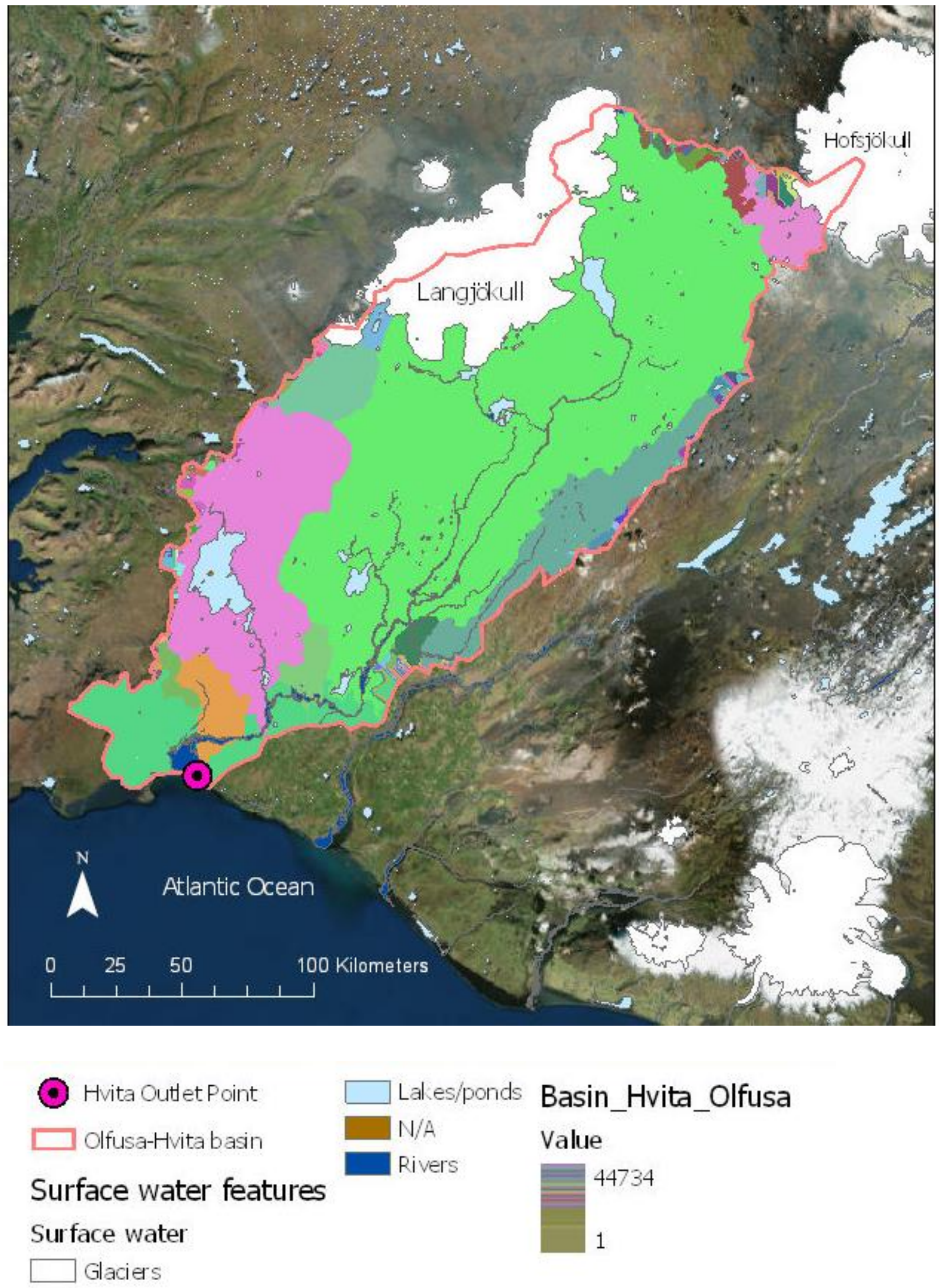

Figure 5. Basin delineation for Hvítá-Ölfusá watershed.

Methods

Datasets

I used three datasets for this project (Figure 3). All three are from Landmælingar Íslands (National Land Survey of Iceland) and are part of IS 50V, an Icelandic digital database developed from aerial photos, SPOT-5 satellite images, and GPS measurements (Landmælingar Íslands, 2017). The first dataset was vector data with polygons of glaciers, ponds/lakes, major rivers, and "N/A," which denoted islands in river channels. The second was a vector line dataset of smaller drainage features (everything except the large polygon rivers from the first dataset) and included both natural features and human-made drainage canals and ditches.

The third dataset was a DEM of Iceland with 30 x 30 m cells. As my analyses progressed, some of the geoprocessing tools either failed to run or did not run correctly, prompting suggestions from colleagues that the DEM may be to blame. On closer examination, I discovered that my elevation model was derived from contour lines rather than directly from imagery. I tried to download higher-resolution DEMs from ArcticDEM and USGS EarthExplorer, but I could not find complete coverage of my study area. I am currently working to obtain a more accurate DEM to use for future analyses.

Analyses

Although my input datasets were fairly complete, I had to fill some gaps first. However, many of these data gaps only became apparent after several failed geoprocessing attempts. Although frustrating to vary inputs and repeatedly carry out the same sequence of steps, these renditions eventually enabled me to troubleshoot and gradually rule out problems until I discovered the underlying glitch in the analyses.

First, I transformed all layers to a WGS 1984 Web Mercator Auxiliary Sphere projection and a GCS WGS 1984 geographic coordinate system. Next, I clipped my datasets from full coverage of Iceland to only my region of analysis. I first tried to derive the drainage basin extent with the Watershed (Ready-to-Use) Tool by creating a point at the Hvítá-Ölfusá outlet at the Atlantic Ocean and importing the geographic coordinates in an Excel spreadsheet into ArcGIS Pro. To correctly display the point, I had to use a WGS 1984 UTM Zone 27N projected coordinate system. Unfortunately, the Watershed analysis repeatedly failed. To speed up processing by shrinking my analysis extent, I created a polygon feature class that completely encompassed my estimated watershed. I clipped the DEM and hydrology datasets to the polygon and ran the Watershed (Spatial Analyst) tool (which failed) and the Basin tool (which worked). In an attempt to further narrow down the basin, I repeated the sequence for three increasingly smaller polygons. Each polygon input produced different basin delineations, although the Hvítá-Ölfusá basin remained fairly similar, with most differences occurring near the polygon edges. The basin differences may be due to my lower-resolution, contour-derived DEM (Figures 4 and 5). In any case, I needed another way to delineate the watershed.

In an article on winter ice jam flooding, Pagneux et al. (2010) included a map of the Hvítá-Ölfusá drainage basin (Figure 6). While the article did not explain how they derived the basin, it is the only published basin delineation I found, so I decided to use it for this project. I used the Georeference tool to input their map into ArcGIS Pro, traced the basin perimeter to create a new feature class, and hid their map by changing its transparency. I then clipped my DEM and hydrology layers to this basin.

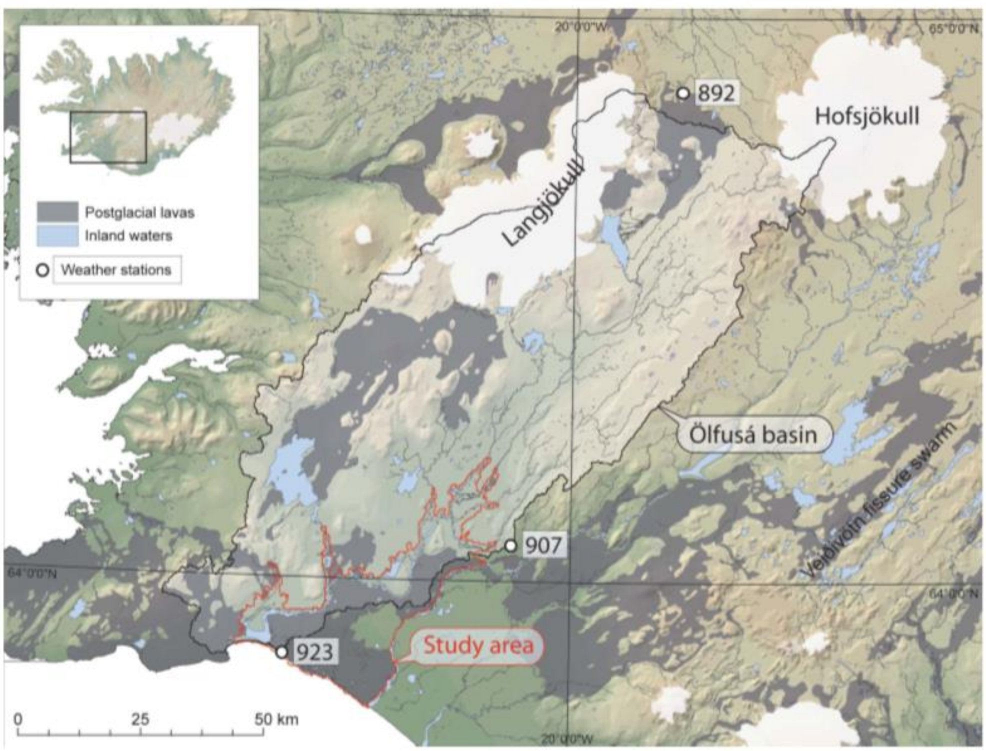

Figure 6. Hvítá-Ölfusá River basin, from Pagneux et al. (2010); red line denotes their study area.

The next step was to streamline the two hydrology datasets, since major rivers were polygon features and smaller streams were line features. After experimenting with some polygon-to-line geoprocessing tools, I eventually capitulated and created a new feature class by drawing lines down the middle of the polygon rivers. I used the Merge tool to combine the datasets. Although the drainage network looked complete on a regional scale, when I zoomed in closely, I realized that not all of my digitized river lines connected to the existing tributary stream flowlines. I started over, this time using the Snapping tool to connect the dots. I also found that many drainage lines from the existing line dataset were isolated and unconnected (Figure 7). I used the Create Feature Class tool to connect as many as possible based on the basemap imagery, but with over 4000 individual stream segments, a comprehensive network was unrealistic for this project. I also realized that the drainage network did not extend through polygon features, so I drew drainage lines through lakes in order to connect the system (Figure 8).

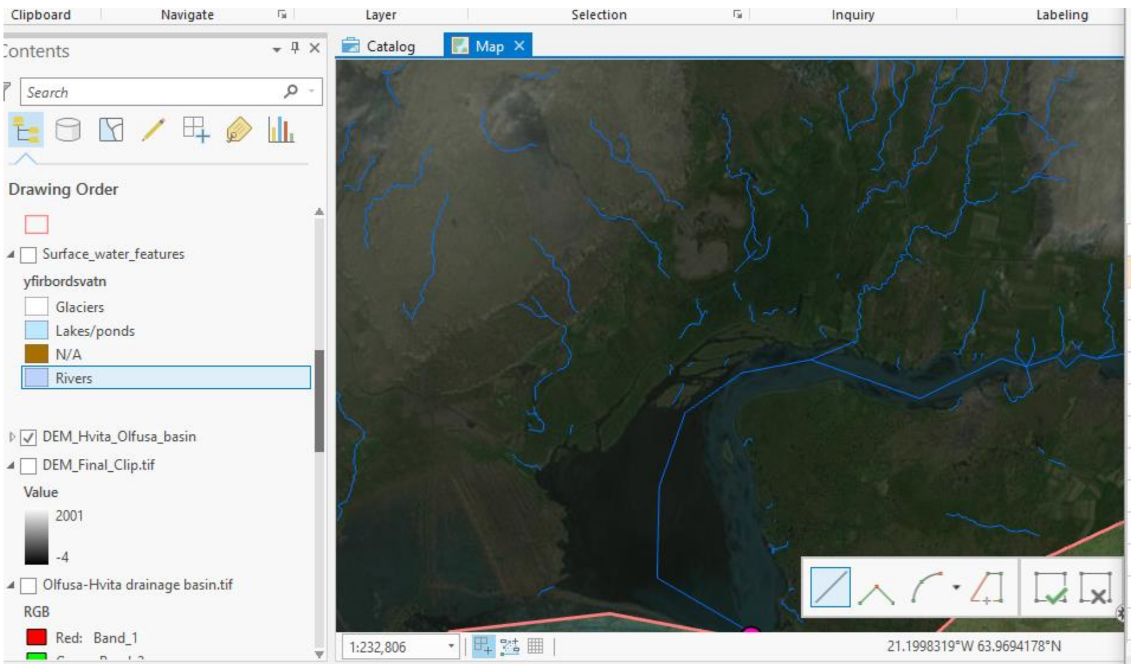

Figure 7. Example of disconnected stream segments near Hvítá-Ölfusá outlet to Atlantic Ocean.

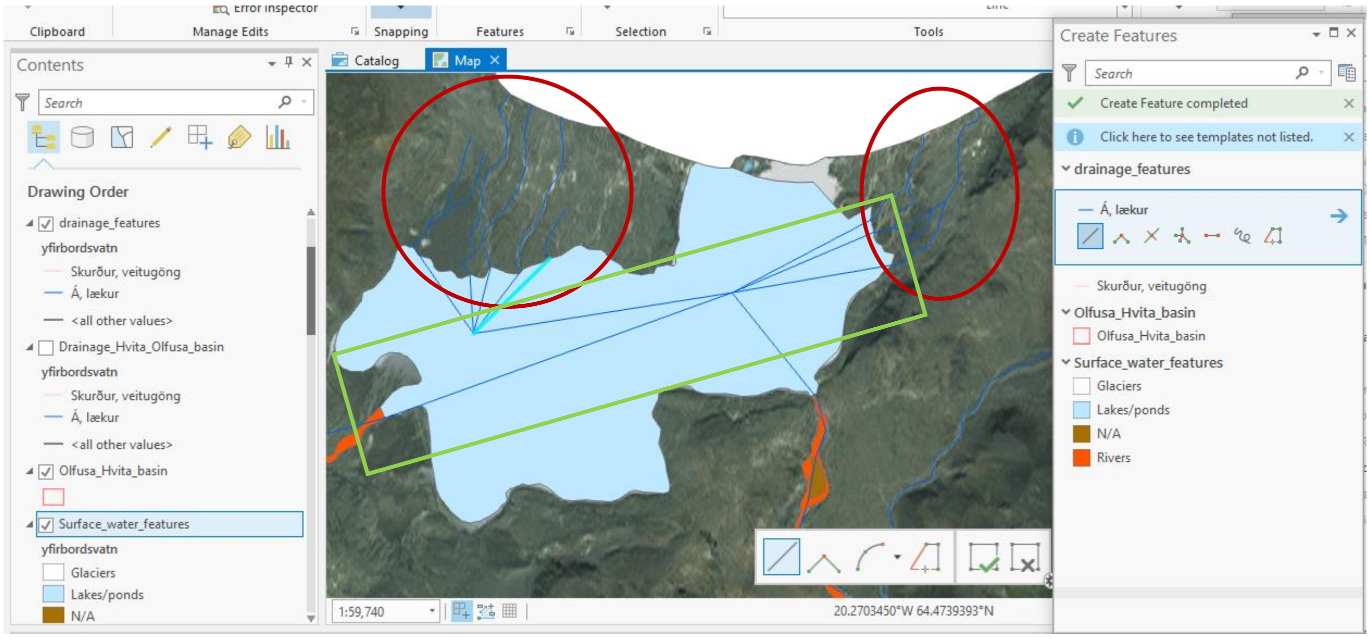

Figure 8. Example of Create Features tool to draw stream segments to connect hydrologic network. The red-circled stream segments were part of the original vector hydrology dataset, but they terminated in the polygon lake feature (Hagavatn, a proglacial lake on the south end of Langjökull). I drew the green-boxed lines to connect the existing stream segments so that the flowlines drained continuously through the lake.

A final obstacle with the hydrology datasets was the thousands of human-made drainage canals and ditches in the lowlands. While these channels contribute to the basin drainage network, I decided to limit my project analysis to natural channels in order to streamline the dataset and speed up processing, so I deleted them from the Attribute Table.

With the hydrology datasets now streamlined, merged, and as complete as possible, I turned my attention to the DEM. First, I used the Fill tool to fill pits in the elevation model. Next, I mapped Flow Direction, which produced accurate pour point directions based on the both the basemap imagery and my field knowledge of the study area (Figure 9).

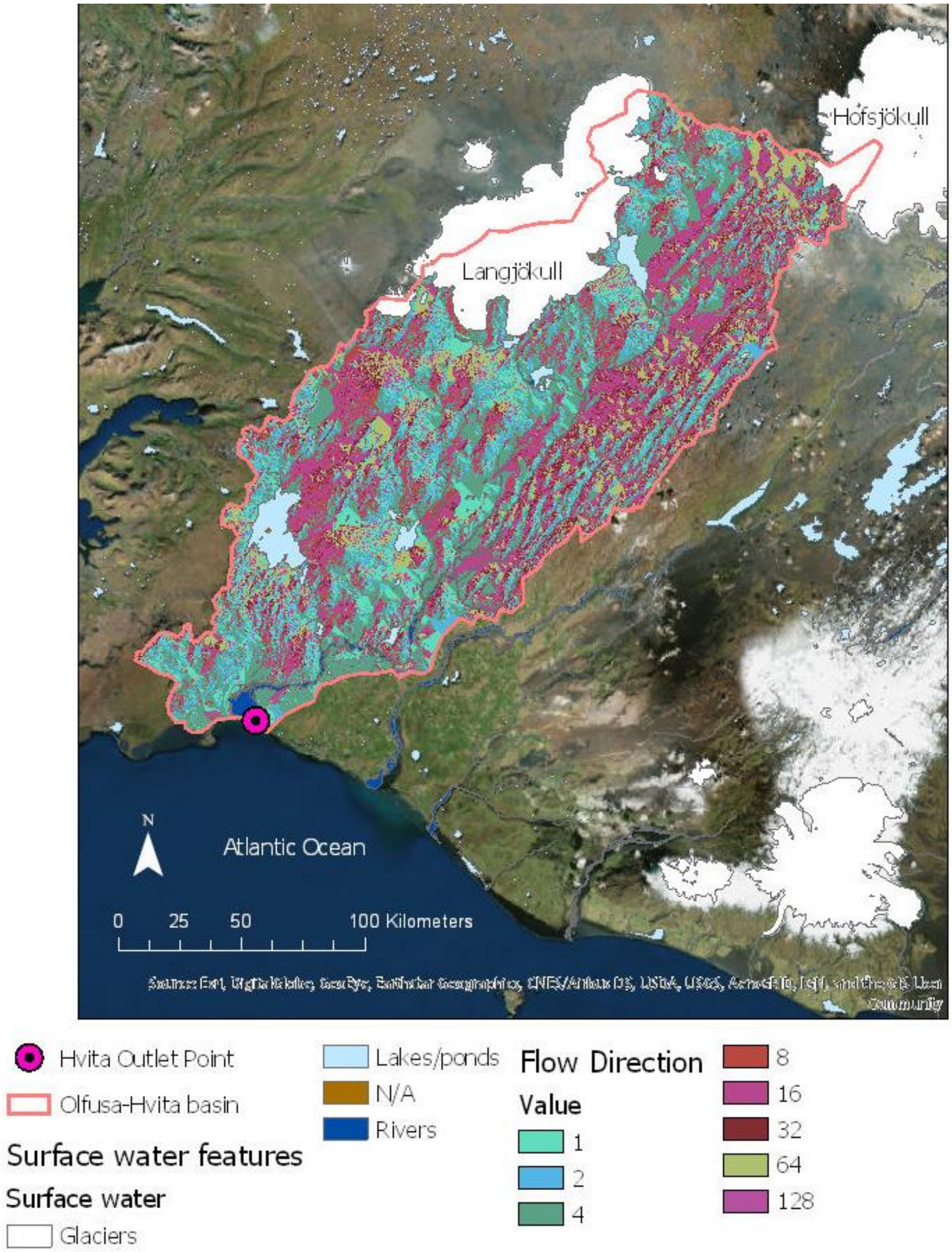

Figure 9. Flow direction raster in Hvítá-Ölfusá basin.

I then mapped Flow Accumulation, which ran successfully, but did not allow me to classify the output into groups of values under the "Symbology" tab; instead, the entire layer displayed a value of 0. I also ran the Flow Length tool with both "upstream" and "downstream" directions of measurement, although upstream worked best since it measured the length of the longest flow path in the basin (Figure 10).

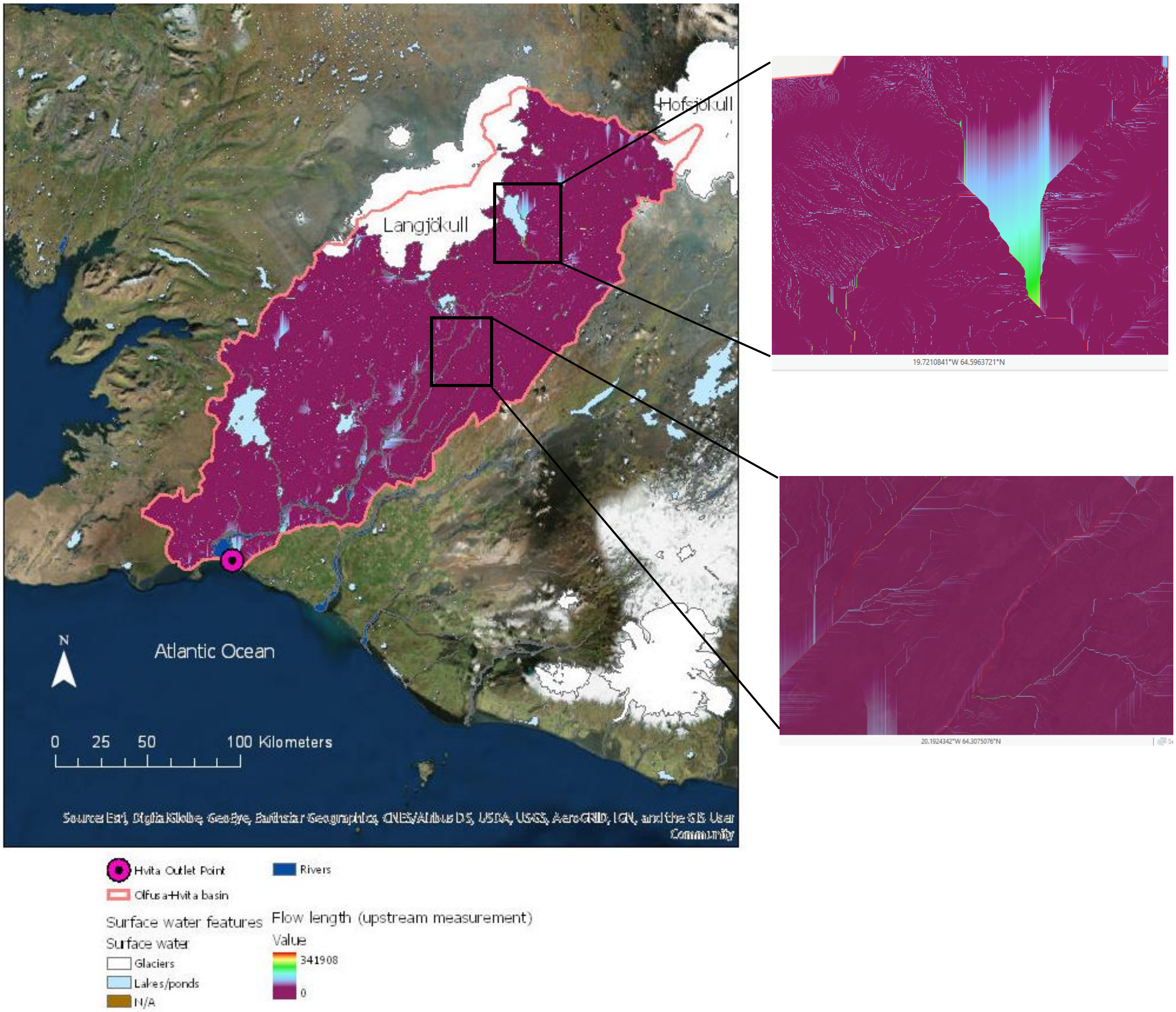

Figure 10. **Left**: flow length (upstream measurement) in Hvítá-Ölfusá drainage basin. **Top right**: close-up of upstream flow length in Hvítárvatn lake; note that outlet has a higher value than further upstream. **Bottom right**: close-up of upstream flow length along Hvítá River (river on right side); note that most of Hvítá is red, denoting higher flow length.

Next, I rasterized the drainage network vector dataset with the Feature to Raster tool. I then used Raster Calculator to map streams with FAC > 5000. However, since the Flow Accumulation tool did not work correctly and 5000 was an arbitrary input—mostly just to see if the tool would work—I did not include this layer in my final interpretation.

Finally, I used the Stream Link and Catchment tools to show individual stream segments and their corresponding catchments (Figures 11 and 12). Since I drew some of these streams by hand, I do not think the results accurately represent basin drainage patterns, especially since the output was 3637 unique stream links and catchments. I also converted the streams to vectors using the Stream to Feature tool and converted the catchments to polygons with the Raster to Polygon tool. Finally, I used the Dissolve tool to create a 1:1 ratio of drainage lines to catchments, but the resulting layer was the same as the "Catchment" output (logically, since the original outputs had a 1:1 ratio).

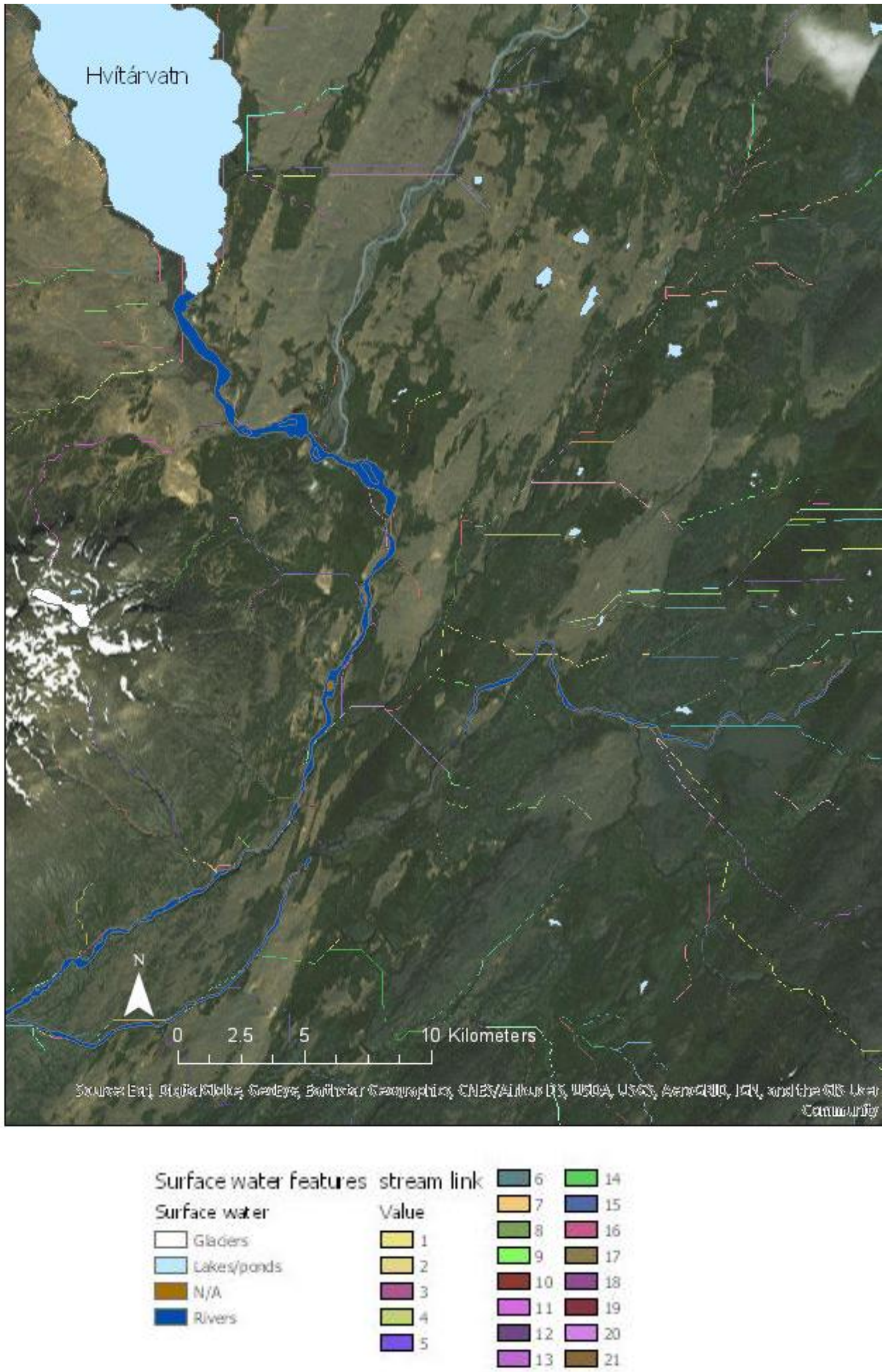

Figure 11. Close-up of stream links for Hvítá-Ölfusá drainage basin. Stream link legend continues for a total of 3637 values.

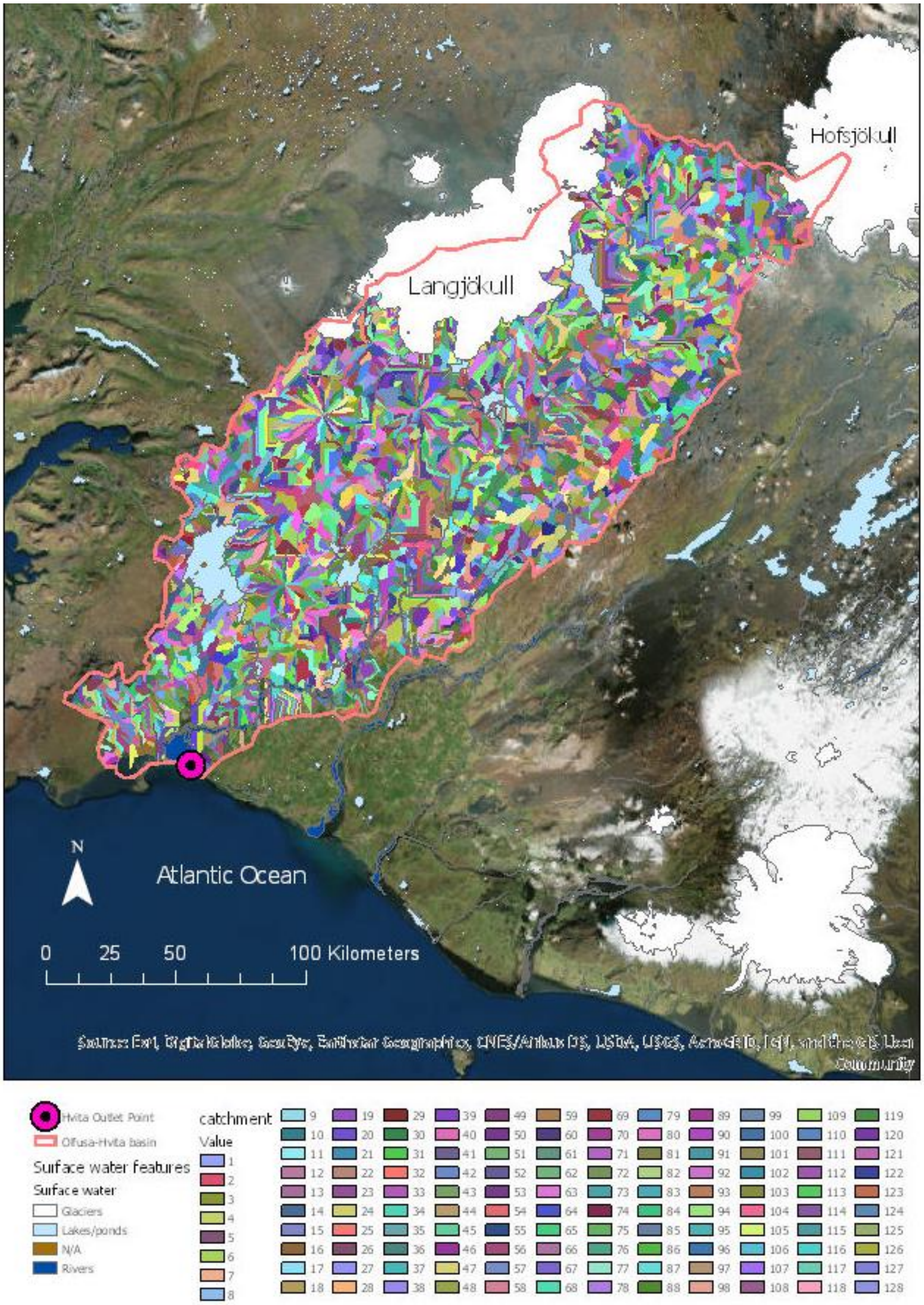

Figure 12. Catchments for stream links in Hvítá-Ölfusá drainage basin. Catchment legend continues for a total of 3637 values.

Results and Discussion

Despite the lack of a high-resolution DEM and a complete hydrologic dataset, my project produced an initial characterization of the Hvítá-Ölfusá drainage basin, setting a strong foundation for future analysis. I created a much more continuous and comprehensive flowline network for the watershed than the existing datasets, and my flowlines are in both vector and raster form.

The Flow Direction tool seemed to yield the most accurate results based on the basemap imagery and my field knowledge of the study area. Although the Flow Accumulation, Stream Link, and Catchment tools ran successfully, they did not seem to work the way they were supposed to, perhaps due to the low-resolution DEM. For example, the resulting 3637 individual stream link and catchment pairings seems too high for a watershed of this size. The Basin tool also generated perplexing results, delineating different drainage basins depending on the input spatial extent. Despite repeated attempts, the Watershed tool did not run successfully when generated from a point at the Hvítá-Ölfusá outlet. Flow Length, however, seemed to produce reasonable results: lakes and major rivers, such as Hvítárvatn and the Hvítá, had higher flow length values, meaning that more upstream cells contributed to their flow. The flow length raster did not exactly overlap with the actual river course (shown on both the basemap imagery and the hydrology dataset), but it was close.

In addition to the Hydrology toolbox, I also calculated basin area, drainage network length, and major river length using Summary Statistics and Add Geometry Attributes. My calculated basin area was 6149 km^2, similar to the 6190 km^2 area reported by Pagneux et al. (2010). Total drainage network length is 8,531 km. The total length of the Hvítá was 130 km.

Future Steps

This project has created a base from which to launch further studies into the Hvítá-Ölfusá watershed. The first step is to obtain a high-resolution DEM. The second is to clean up the hydrologic dataset; for example, some stream segments snapped to a vertex near the end of a drainage feature rather than the endpoint, leaving small segments of streams dangling off the end. A more pressing problem is the isolated drainage lines that are not connected to the basin flowline network. On-the-ground field surveying, higher-resolution satellite imagery, aerial photographs, and lidar could help to complete these drainage networks.

Another future line of inquiry is to investigate water budgets in the Hvítá-Ölfusá basin. I plan to search for precipitation, snowfall, glacier change, and stream gage data. This could enable me to quantify water inflows (e.g. precipitation, snowfall, glacial meltwater, and spring sources) and outflows (e.g. infiltration and evapotranspiration). The Icelandic Meteorological Office (IMO) has at least 15 stream gages in the watershed collecting measurements such as flow discharge, water level, temperature, and electrical conductivity (IMO, 2017). While real-time data is publicly available online, I have not yet found compiled datasets of stream gage measurements. Furthermore, researchers estimate that if current climate trends continue, Langjökull will be gone in 150-200 years (Björnsson, 2017). Where will that meltwater go? Scientists have measured climate and ice cap mass balance in Iceland for decades, resulting in an extensive dataset. These data could be incorporated into hydrologic maps using ArcGIS in order to gain a deeper spatial understanding—and model future predictions— of glacial meltwater contribution to the drainage basin.

I would also like to draw on the Groundwater toolkit to study groundwater origin and transport in the Hvítá-Ölfusá watershed. Iceland's porous volcanic rocks facilitate groundwater transport, and the island is dotted with natural springs. It is a significant and understudied component of Iceland's drainage network.

Conclusion

My initial goals for this project were to characterize the Hvítá-Ölfusá watershed and use HAND (height above nearest drainage) calculations to map inundation area for different flood magnitudes. However, the challenges with my DEM and hydrologic datasets scaled back the scope of the project. Although I will need to re-run analyses once I get a higher-resolution DEM, this project produced an improved hydrology dataset and an initial characterization of the watershed, creating a solid foundation off of which to build future ArcGIS analyses for my dissertation project.

This project familiarized me with the Hydrology toolkit through repeated runs and troubleshooting. It also highlighted the importance of using accurate datasets and underscored the large amount of work required to troubleshoot problems and manipulate data, while also illuminating the vast potential of this incredible spatial resource. The Hvítá-Ölfusá watershed is a crucial yet understudied link in Iceland's hydrologic network. It occupies an important role in spheres ranging from tourism to agriculture, jökulhlaups to winter ice jam floods, and bird nesting sites to fish habitats. This watershed will likely change significantly as climate change continues to rapidly melt much of its source glaciers. This project—and my dissertation research—shed light on this significant and beautiful region.

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